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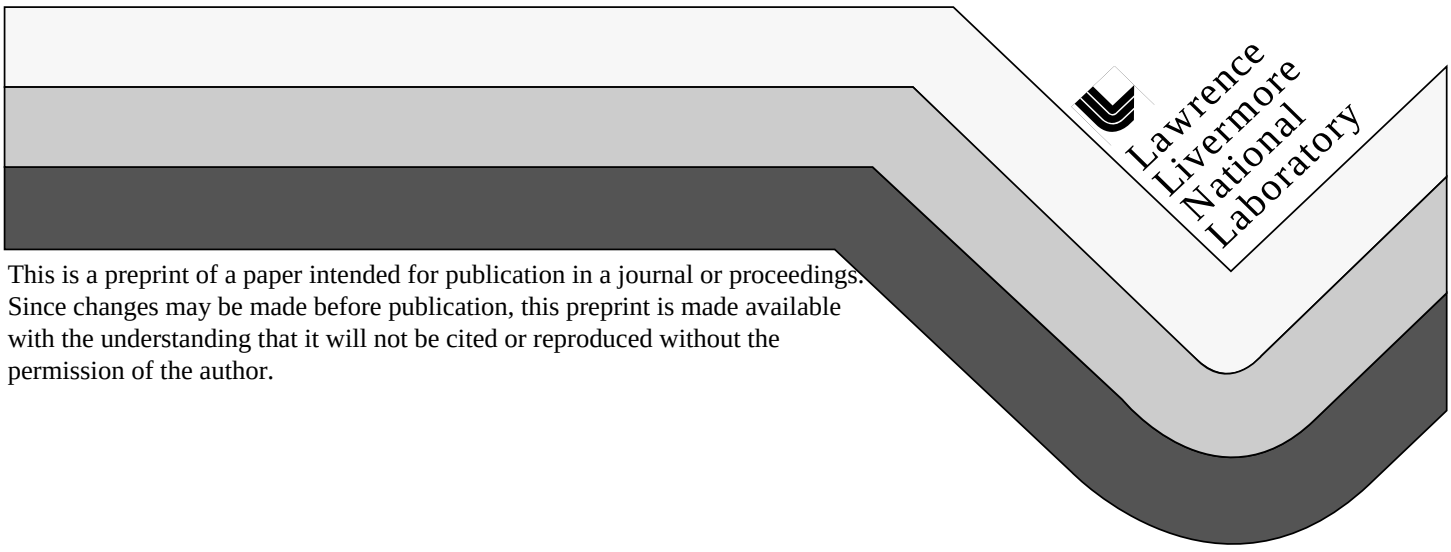

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The vision of sustainability is easily understood in its most general terms as achieving a continuously improving quality of life, all life, into the indefinite future. It is also easy to see that some ongoing human activities are carrying us toward that goal and that some are not, are in fact going to prevent its achievement if they continue. Beyond these generalities, it is often difficult to determine whether specific innovations, technological or social, are really beneficial and how to redirect those that are not.

Industrial ecology is the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution.[1] The foreseeable scientific and technological needs of industrial ecology span from understanding the totality of complex systems to specific innovations and information that are needed in particular applications. In this paper we will first discuss the challenge offered by natural and anthropogenic systems in all of their complexity and then will indicate some areas of research in which specific scientific and technological needs are identifiable.

Complex Systems

Human communities are complex systems with inputs, outputs, and complex internal functions and flows of material, energy, and life activity. They are studied and modeled independently by city planners and engineers, by economists and social scientists, and by environmental scientists, but not wholly as organic, nonlinear, complex systems, as living

entities that metabolize, grow, suffer disorders, and adapt. We are not yet capable of thinking of communities in terms of their internal ecology or their extended environmental interactions and effects.

Our knowledge of other complex systems, though evolving, is also primitive in comparison to the needs for achieving wise stewardship of the Earth. For example, we are beginning to understand the flows and pools of carbon in the atmosphere, oceans, soil, and living systems; we are measuring and modeling the effects of burning fossil fuels as an input to the global carbon system; but we have not yet begun to understand the specific effects and adaptations that global carbon cycle changes will cause in living systems, or even inorganic systems.

Another example is water and water systems. Water is emerging as one of the commodities whose efficient and equitable use is critical to the stability of the human community. In Africa, China, India, Turkey, the Middle East, and even the western United States, critical situations are arising, partly because the interactions between human activity and regional precipitation, surface and groundwater flows and pools, and agricultural, industrial, and residential systems are not yet understood.

The understanding and management of complex systems is the overarching challenge for the scientific community in developing industrial ecology. The examples given here - communities, carbon, and water - are themselves, in fact, only parts of greater systems. The Netherlands, for example, is attempting to move toward sustainability as a national goal and is making admirable progress. Still, the Netherlands has realized that its internal activities reach remote parts of the world through its substantial imports of both raw and finished goods. The Netherlands is itself a subsystem of the global system. The point is not to diminish their vision or their achievements, but to emphasize the complexity of the systems involved and the sophistication of the science, technology, and societal responses that are needed.

Global Security

A brief comment on global security is in order. Obviously, achieving sustainability is far more difficult in the destructive context of international or even intra-national hostility and war. Integration of the concepts and goals of sustainability and security will increase as

globalization increases. Global security will increasingly involve understanding of the systems just mentioned and mitigation of the underlying ecological sources of conflict, such as, population instabilities, energy resource limitations, water quality and quantity deficiencies, regional and global air pollution, global climate changes, and major natural calamities. This trend is an explicit assumption in the National Security Science and Technology Strategy published last year by the US National Science and Technology Council. The need for industrial ecology is driven both by the desire for continued improvement in the quality of life and by the realization that serious global disruptions will occur without this approach.

Energy for Transportation

Let me turn now to specific areas of science and technology development which support the objectives of industrial ecology, namely, primary and secondary energy resources, materials, environmental technology, and biology. I will use examples with which I am familiar because they are ongoing activities at Lawrence Livermore National Laboratory. Many other examples from private industry, universities or other laboratories are some cause for optimism concerning our future.

One of the principal emission generators in the developed countries of the world is our transportation systems, now based almost entirely on fossil fuel. Several hydrogen, electric, and hybrid alternatives are under development.

If the hydrogen in a gallon of water is separated and then burned back to water, the burning yields the energy equivalent of about a half of a gallon of gasoline. This water to water fuel cycle is zero emission if the energy needed to separate the hydrogen, and the ensuing combustion of hydrogen are both clean. The burning of gasoline is, of course, not clean in this sense, and produces CO_2, a greenhouse gas, and other particulate and gaseous pollutants. Did you realize that 90% of the material used in the life cycle of a car is the non-recyclable burned gasoline; only the 10% steel and plastic have the possibility of being reused or recycled. In fact, each of you will use more than 100 tons of gasoline in your lifetime of driving. Hydrogen is a good alternative which can reduce the need for nonrenewable fuel, increase the recyclability of transportation equipment

by a factor of 10, and decrease transportation system emissions to near zero.

Hybrid electric vehicles use the hydrogen energy to generate electricity which is then stored in flywheel or ultra capacitor systems, which in turn power the vehicle by means of electric motors. The intermediate energy storage allows the vehicle's hydrogen powered electric generator to operate continuously at peak efficiency while the vehicle's power requirements vary. Similarly, the electrolytic production of the hydrogen fuel can act as a load-leveling intermediary for the utility electric source, thus allowing utility power to be used on an as available basis, and absorbing the variability of many renewable primary energy sources.

Another option is the refuelable battery, such as the zinc-air battery which can produce five times the energy per unit weight of a lead acid battery and can be "recharged" in about 10 minutes. The battery works by generating electricity when zinc pellets react with the battery electrolyte. The battery is refueled by draining its electrolyte, and loading in fresh electrolyte and zinc pellets. Both the zinc and the electrolyte are wholly recoverable. There are no emissions from this battery nor from the electrolytic zinc and electrolyte recovery processes. The weight of such batteries along with the motors and drive units for a 300-mile-range vehicle weigh slightly more than the gas tank, engine, and transmission for a current-technology car of the same range and peak power.

These technologies in various combinations have the goal of an efficient, safe, and low or zero emission vehicle that competes in cost and performance with current gasoline powered cars. Some of this work is being carried out under the Partnership for a New Generation of Vehicles with US auto makers.

Fusion Energy

If hydrogen is burned thermo-nuclearly in a fusion reaction, rather than chemically in normal combustion, the energy equivalent of the hydrogen, actually deuterium, in a gallon of water is about 500 gallons of gasoline. This "burning" occurs when the nuclei of the hydrogen atoms collide and fuse to form helium. The inherent fusion energy yield per unit of fuel mass is potentially a million to ten million times greater than the energy yield for chemical combustion.

This process has two remarkable advantages. First, the energy available on Earth from hydrogen fusion is virtually unlimited. And second, the inherent "emissions" or residues are zero, although the design of a practical reactor will involve the generation of some radioactive waste.

Livermore is the world leader of the use of lasers to drive controlled fusion reactions and is in the process of designing and building a system, the National Ignition Facility, which will demonstrate the scientific feasibility of this process by achieving energy gain from a single-shot micro-fusion reaction. The competing international magnetic fusion program has as its goal the continuous thermo-nuclear burning of a fusion plasma contained in a magnetic field.

Granted that fusion energy is not easy to achieve. Magnetic fusion has been a goal for 40 years and laser fusion for 25. Even when these are demonstrated in prototype systems, the engineering of reactors will be extremely difficult. But it will happen eventually.

When clean, unlimited fusion, and undoubtedly also advanced nuclear fission, and, hopefully, solar-derived electric energy sources are coupled with hydrogen or battery transportation systems, the essential energy needs of a zero emission sustainable society will be satisfied.

Materials

A key building block for industrial ecology is a National Materials Data Base focused on the environmental and economic impacts of new and existing materials. The database should be easily accessible to designers and compatible with computer aided design tools and accounting systems, and should provide environmental load and cost data on the extraction, refinement, processing, and product manufacturing, use, recycle, and disposition for the constituent materials. Clearly, health and ecological hazards should be highlighted.

In June, a conference hosted by the Livermore Laboratory brought together 100 experts from industry, national labs, universities, and federal agencies to examine specifically the environmental data needs for materials used in the microelectronics and automobile industries, because these industries have been very active in addressing environmental issues and are significantly “up the learning curve”. An action team of these industry leaders and the other participating groups will look for incubation of this

data base by IEEE, ASME, and AIChE, would like to develop long-term federal support, and is consensus-building on the needs and uses of this database.

Beyond understanding the environmental loads of available materials, new materials are needed which perform new functions, improve product environmental and economic efficiency or life, and are efficiently reusable or recyclable. One interesting example is a class of materials called aerogels, which are solids that are so porous that they are about the same density as air. Aerogels made from silica are the best thermal and electrical insulators known. Aerogels made from carbon are able to store electrical energy at extremely high density in ultra capacitors. Aerogels made from agar are lighter than air and edible. When configured as modular voltaic liquid filters, aerogels have been used to purify salty water with an efficiency which should be economical on a wide range of scales. Given their lightness, unique properties, systems versatility, and environmental friendliness, aerogels should find many industrial ecology applications.

Cermet is another example. Cermet is a ceramic-metal alloy, one which is tougher and more durable than steel and as light as aluminum, uncorrodable, non-toxic, and superior to glass or metal for many high-stress uses, such as engine parts. The lightness and durability of cermet could reduce life-cycle materials use; and its inertness that could minimize disposal problems until recycling or reuse systems are developed.

Superplastic steel is extremely small-grained steel that can be formed to the final product shape with good enough precision to require no machining, thus producing little or no waste.

The environmental advantages of these new materials was serendipitous, not the principle intention of the inventor. In the future, sustainability should be one of the materials designers' primary goals.

Environmental Technology

The purpose of environmental technology for sustainability is to facilitate the efficient recovery and reuse of residue streams, and to enhance the economic and environmental efficiency of economic activity. Much of current environmental technology development is focused on the remediation of contaminated sites. However, the sensors for the detection

of pollutants and the cleanup techniques are adaptable to material and manufacturing processes, as methods for cleansing and transforming used material for recycle, alternate use, or harmless disposal. For example, microbial destruction of volatile organic compounds (VOCs) can be used to either cleanse reusable liquids or porous materials, or to transform the contaminants into useful materials like alcohol from methane or biomass. Sensors developed for detection of pollutants in soil and ground water can also be used on-line as process and environmental quality monitors.

Bioscience

Bioscience at Livermore is concentrated on genomics, the decoding and study of the functions of DNA, primarily of humans, but expanding to animals and plants. One goal is to understand how environmental insults damage DNA leading to cancer and other health problems. In some cases, DNA is able to repair itself and counter specific environmental threats. We have now mapped human chromosome 19 entirely, and have identified about 500 genes and genetic markers; three of the genes are repair genes which can cure specific genetic damage. Understanding the fundamental strengths and weaknesses of life forms is essential in establishing environmental thresholds and priorities.

Another application of genomics is the improvement of human health and the engineering of plants and animals to increase their productivity and environmental performance, that is, their disease and pest resistance, with less or no chemical assistance.

This enabling technology will also be used to improve industrial processes, for example, in enzymatic cleaning and chemical manufacturing processes.

Finally, genomics will eventually be the basis for measuring and managing biodiversity. Genetic codes will comprise the catalogue of life forms and functions. The current libraries of genetic fragments and the genome databases are the initial phase of this development.

Conclusion

Scientific and technological communities have a significant role to play and responsibility for the development of global sustainability. Or, turning the phrase, sustainability is not possible without a substantially

improved science and technology basis for industrial ecology. And our responsibility is not limited to the laboratory or the computer; society needs data and understanding of complex ecological issues to govern itself in a sustainable manner. We should:

- Support and develop multi-disciplinary programs which create the scientific basis for understanding natural and anthropogenic complex systems and for the development of environmentally and economically efficient technology.
- Demonstrate a systems-based approach to science and technology issues which is life-cycle comprehensive, which integrates environmental considerations, and which promotes the conservation of natural resources.
- Encourage the development of responsible, technically and scientifically valid, cost-effective environmental policies, laws, and practices.

Reference

[1]Industrial Ecology, T. E. Graedel and B. R. Allenby, Prentice Hall, Englewood Cliffs, New Jersey 07632, 1995.

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